

## **A-4 Session “Beam loss & halo dynamics”**

**13:30 - 13:50 Yoichi Sato**  
**Session Chair**

**Lead talk: Beam Loss and Halo Dynamics**  
**Session Question**  
**Answers of J-PARC Main Ring**

**13:50 - 14:05 Trent Thompson**

Observations of mismatch-driven halo  
in 2.5 MeV H- beam at the SNS Beam Test Facility

**14:05 - 14:20 Shouyan Xu**

Space Charge Effect Simulation and Tune Optimization  
for Reducing Beam Loss at CSNS

**14:20 - 14:35 Esmaeil Ahmadi**

Experimental and Simulation Studies of  
Non-linear Resonances in the ISIS Synchrotron

**14:35 - 15:00 Yoichi Sato**  
**Session Chair**

Discussion Session A-4

# Question to A-4 Session

Q: How to design a next-generation highest-intensity facility?  
from the particular view point of the A-4 session topic  
**“Beam loss & halo dynamics”**

## Session Chair (Y.S.) NOTES

Define **“Beam halo”**

as a part of beam **touching physical aperture or collimators**  
in this lead talk.

Let's **isolate** beam loss sources:

**Beam halo developments and beam instabilities**  
as much as possible  
even though they are relating each other deeply.

# Y.S.'s view for the Question

Q: How to design a next-generation highest-intensity facility?  
from the particular view point of the A-4 session topic  
“Beam loss & halo dynamics”

**Beam halo** in A-4 = a part of beam touching physical aperture or collimators

## To reduce the beam halo development

| Measures                                 | Initial Design      | Post Design + Study Time |
|------------------------------------------|---------------------|--------------------------|
| A) Enlarge physical / dynamic aperture   | Main devices        | Optics Improvement       |
| B) Avoiding / killing transition energy  | Arc design          | ---                      |
| C) Avoiding the betatron resonance lines | Base Tune           | Tune survey              |
| D) Suppressing betatron resonances       | Place of post-works | Adding Corrections       |
| E) Removing resonance sources            | Lattice design?     | Lattice Re-design?       |
| F) Linear mitigation of SC               | Higher energy       | Longitudinal control     |

## Measures for insability, beam loss source but not from the beam halo development

*Impedance budget control, Sllipage opt., FB system, Chromatic control, Longitudinal control, ...*

*Mixture of **initial** and **post** works*

**Initial works are very important, but Post works can be performed some using Margines.**

**Challenge cost limits always to earn margines for our future!**

# Discussion for Our Future

Q: How to design a next-generation highest-intensity facility?  
from the particular view point of the A-4 session topic  
“Beam loss & halo dynamics”

**Beam halo** in A-4 = a part of beam touching physical aperture or collimators

## To reduce the beam halo development

### Measures

- A) Enlarge physical / dynamic aperture
- B) Avoiding / killing transition energy
- C) Avoiding the betatron resonance lines
- D) Suppressing betatron resonances
- E) Removing resonance sources
- F) Linear mitigation of SC

### Initial Design

- Main devices
- Arc design
- Base Tune
- Place of post-works
- Lattice design?
- Higher energy

### Post Design + Study Time

- Optics Improvement
- 
- Tune survey
- Adding Corrections
- Lattice Re-design?
- Longitudinal control

Enough?

### Measures for insability, beam loss source but not from the beam halo development

Impedance budget control, Slippage opt., FB system, Chromatic control, Longitudinal control, ...

Enough?

Mixture of *initial* and *post* works

**Initial works are very important, but Post works can be performed some using Margines.**

**Challenge cost limits always to earn margines for our future!**

Agree?

## Answers of J-PARC Main Ring to Q of A-4 Session “Beam loss & halo dynamics”

- Introduction and Answer lists in J-PARC Rings
- History of the Answers in J-PARC Main Ring

**Yoichi Sato (KEK/J-PARC), A-4 Chair**  
SPACE CHARGE 2026 @Oxford U, UK

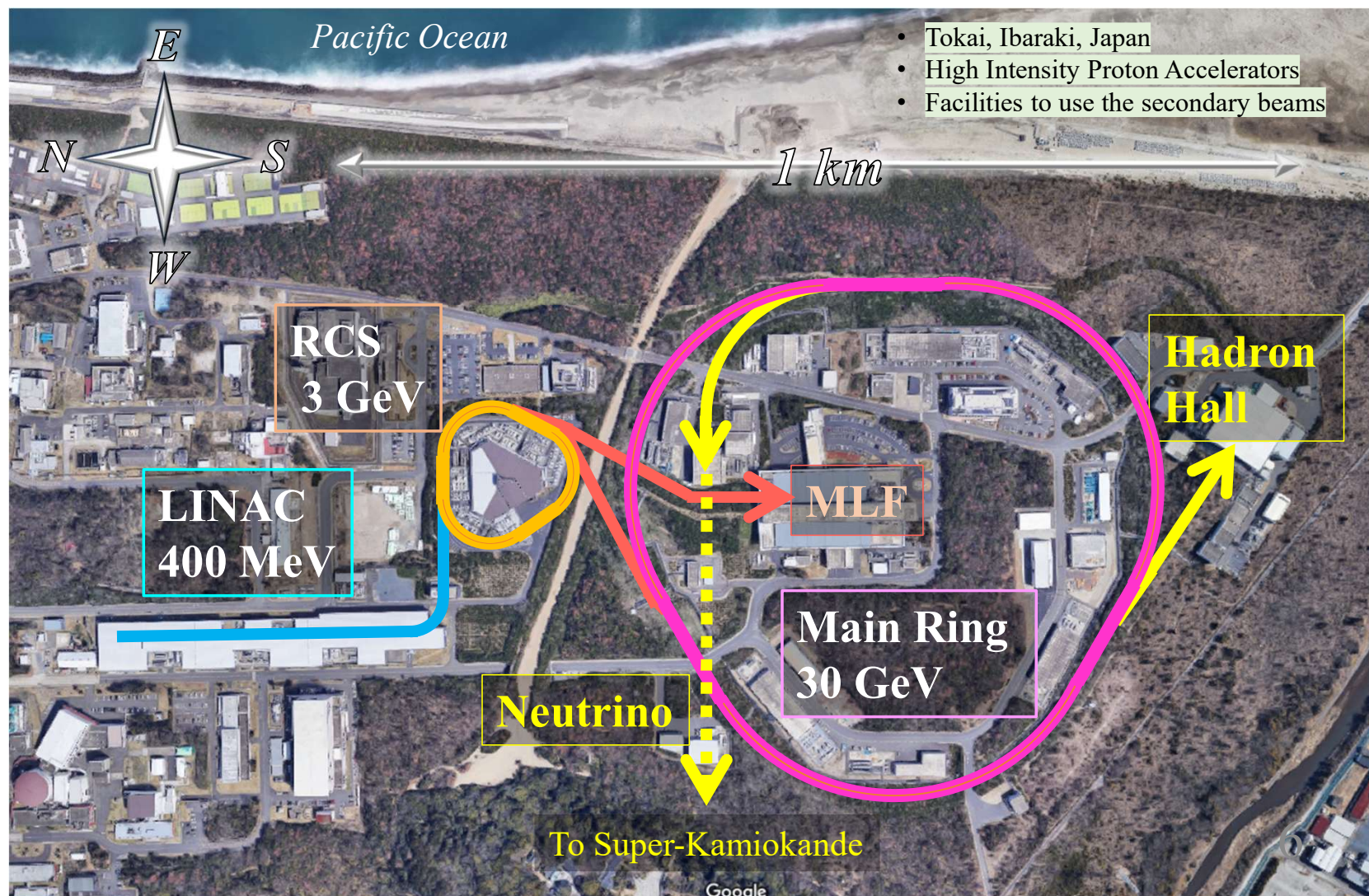
Oct. 2<sup>nd</sup>, 2026

<https://indico.global/event/15713/>

# Japan Proton Accelerator Research Complex

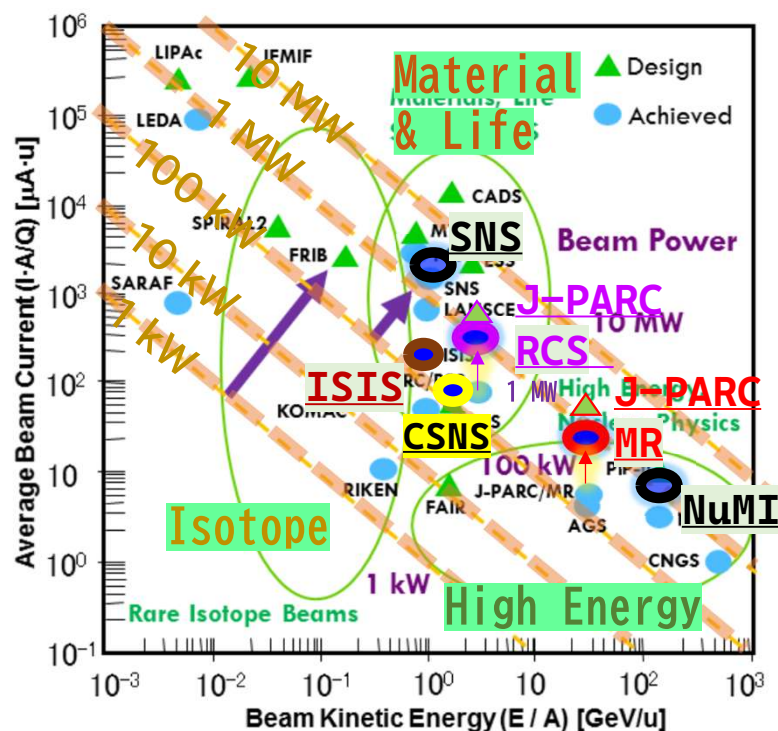
Operated by  
Japan Atomic Energy Agency  
(JAEA) and  
High Energy Accelerator  
Research Organization  
(KEK)

Cutting-edge  
scientific researches  
are being realized  
by utilizing  
the plenty & diverse  
secondary particles  
(Neutron, Muon, Kaon,  
Pion, Neutrino, ...)  
produced by  
the world's highest-  
class high-intensity  
proton accelerators  
(MW-class).



# World Intensity Frontiers (~ GeV or higher)

Averaged Beam Power = (Ave. Current) \* (Energy) --- Good INDEX of Accelerator Performance



World Intensity Frontier Hadron Accelerators

●: Achieved by 2014, ●: by JFY2025

Jie Wei, IPAC2014

Updated by Yoichi Sato

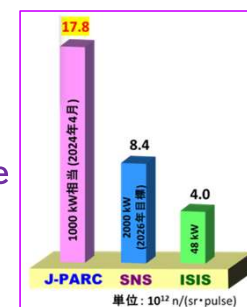
2026/10/02

Yoichi Sato, Lead talk of A-4 Session, Space Charge 2026

~ 1 GeV P+ --- Material & Life Science

SNS (US) 2.0 MW at 1.3 GeV ← WR: Beam Power

J-PARC RCS 1 MW at 3 GeV → WR: Neutron power/pulse  
Near Future : 1.5 MW



> 10 GeV P+ --- High Energy Elementary Particle / Nuclear

NuMI (US) 1.05 MW at 120 GeV

J-PARC MR-FX 0.9 MW at 30 GeV Near Future : 1.3 MW (2028)  
NU with 2.3-2.7E+14 ppp beam from MR ← WR: Protons/pulse

J-PARC MR-SX 101 kW at 30 GeV ← WR: SX-Beam Power  
Near Future : > 150 kW

HD with slow extraction beam in ext.  
SX 8.9E13 ppp, efficiency 99.65% ← WR: SX-efficiency

Q: How to design a next-generation highest-intensity facility?  
from the particular view point of the A-4 session topic  
“Beam loss & halo dynamics”

**Beam halo in A-4 = a part of beam touching physical aperture or collimators**

## To reduce the beam halo development

### Measures

- A) Enlarge physical / dynamic aperture
- B) Avoiding / killing transition energy
- C) Avoiding the betatron resonance lines
- D) Suppressing betatron resonances
- E) Removing resonance sources
- F) Linear mitigation of SC

### Initial Design

- Main devices ✓
- Arc design ✓
- Base Tune ✓
- Place of post-works
- Lattice design?
- Higher energy ✓

### Post Design + Study Time

- Optics Improvement ✓
- 
- Tune survey ✓
- Adding Corrections ✓
- Lattice Re-design? ✓
- Longitudinal control ✓

### Measures for insability, beam loss source but not from the beam halo development

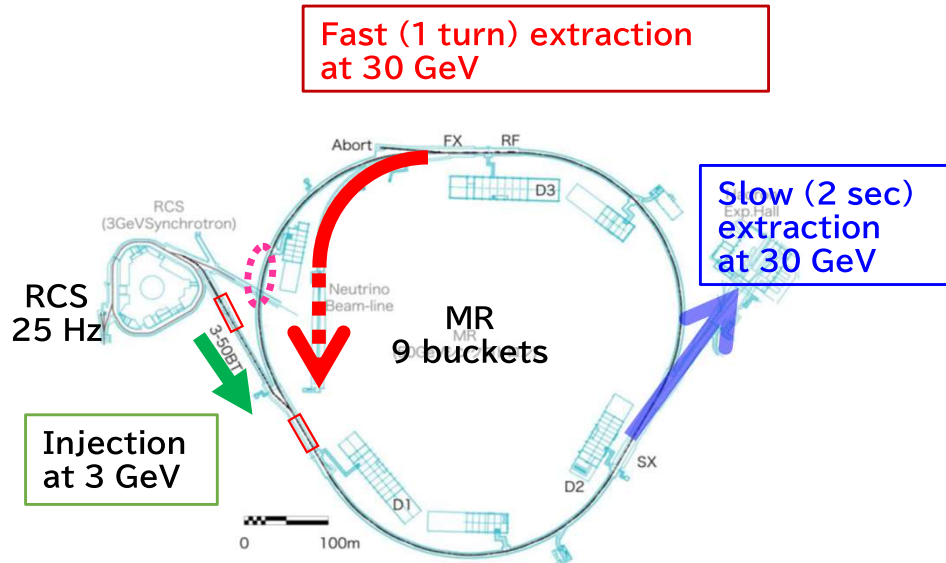
Impedance budget control, ✓ Sllipage opt., ✗ FB system, ✗ Chromatic control, ✗ Longitudinal control, ...

Mixture of *initial* and *post* works

**Initial works are very important, but Post works can be performed some using Margines.**

**Challenge cost limits always to earn margines for our future!**

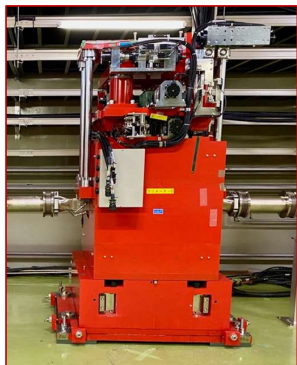
# Parameters of Main Ring the Ring Formerly Known As the 50-GeV Ring



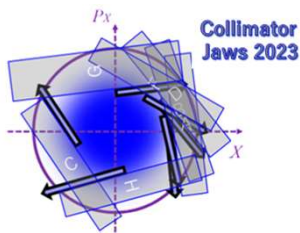
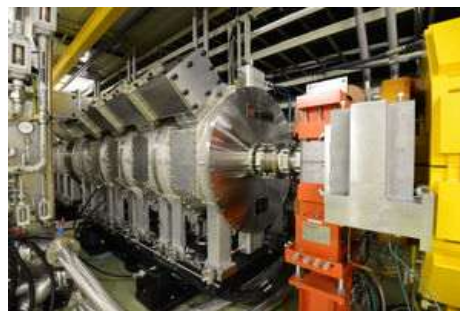
|                   |               |
|-------------------|---------------|
| Circumference     | 1567.5 m      |
| Injection energy  | 3 GeV         |
| Extraction energy | <b>30 GeV</b> |
| Injection time    | 0.13 s        |
| Acceleration time | 0.65 s        |
| Super-periodicity | 3             |
| harmonic          | 9             |
| Number of bunches | 8             |

World Records  
 Protons per pulse  
 (To NU)  
 SX-power,  
 SX-Efficiency  
 (To HD)

240~270 TP (~ 4 us long pulse) circulate inside MR.  
 1 turn acceleration ~ 260 keV. 150,000 turns for injection and acceleration



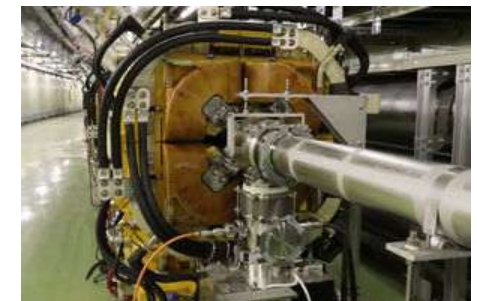
7 Collimators in MR  
 12 Collimators in Injection BT



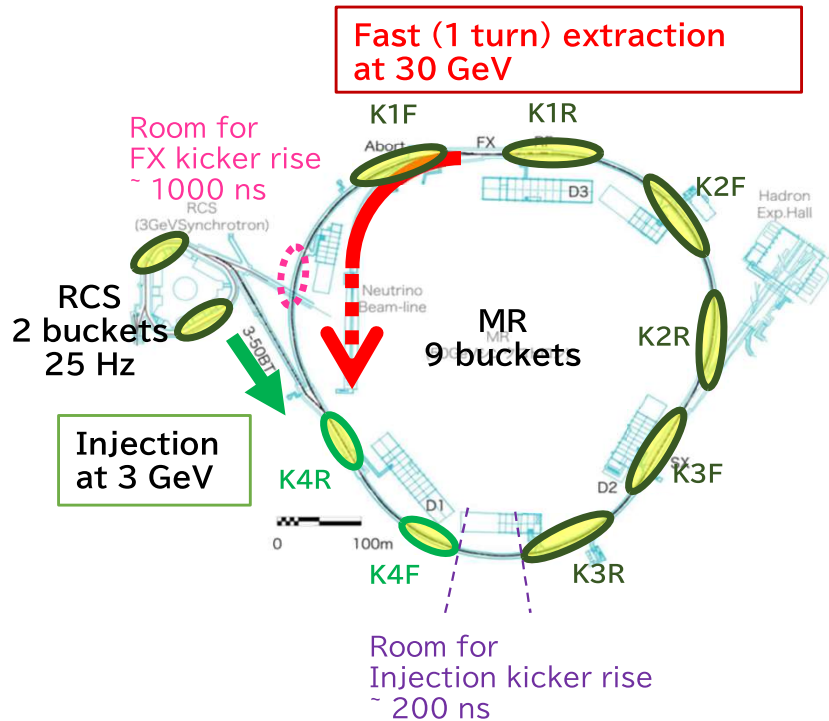
RF cavity  
 10 for Fundamental,  
 2 for 2<sup>nd</sup> harmonic



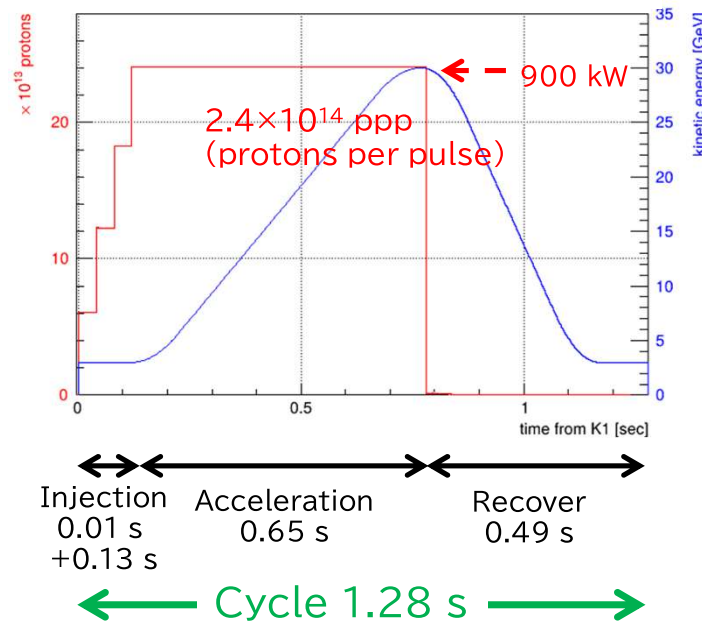
Bending magnet  
 Total 96 magnets



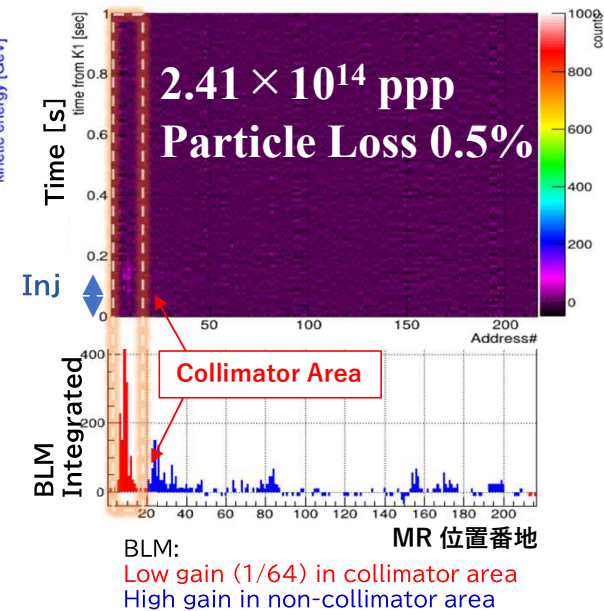
Quadrupole magnet  
 Total 216 magnets



Circulating Protons (DCCT)  
Magnet/RF ramping pattern



Beam loss distribution



4-time-injection from RCS (2 bunches each).  
Magnet/RF patterns are synchronized with beam K.E.

|               | 3 GeV             | → 30 GeV   |
|---------------|-------------------|------------|
| Bucket size:  | 598 ns            | → 581 ns   |
| RF freq:      | 1.67 MHz          | → 1.72 MHz |
| Bunch/Bucket: | 25~60%            | → 10%      |
|               | Dual harmonic RFs |            |

- Beam loss mainly occurs during injection and low energy period.
- Particle Loss ratio < ~1% for maintenance capability.
- Collimator area collects ~98% beam losses.

Beam Power  $\propto$

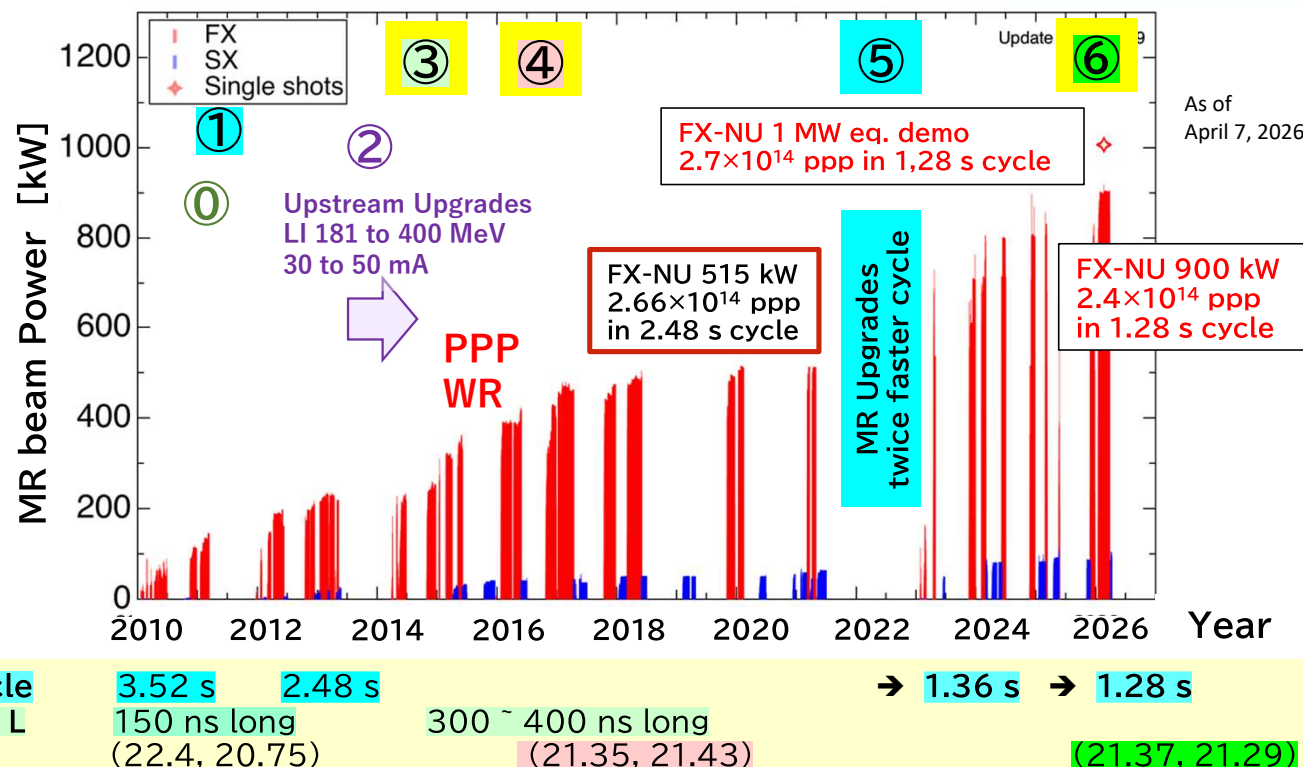
$\frac{\text{Protons per pulse}}{\text{Cycle length}} \times \text{Beam Energy}$

## More Protons :

- Resonance, Space charge, Resistive wall, beam loading, ...

## Faster cycle :

- Hardware technology and facility limits



As of April 7, 2026

⑦

Needs better 3-fold symmetry to suppress non-schematic betatron resonances

1<sup>st</sup> BBA/BBGC activities 2009 – 2014 & TxT Base Optics Corr ~2021:  $\Delta\beta/\beta \sim 5\%$   
 New Optics Corr. method of Orbit Resp. Matrix Base 2023~:  $\Delta\beta/\beta < 2\%$

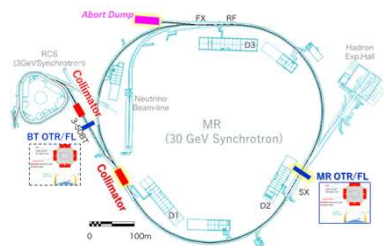
①

Faster cycle approach is effective, if beam optics can be kept.

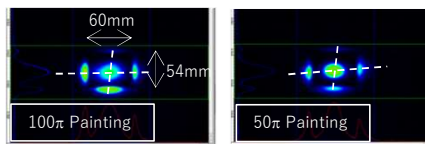
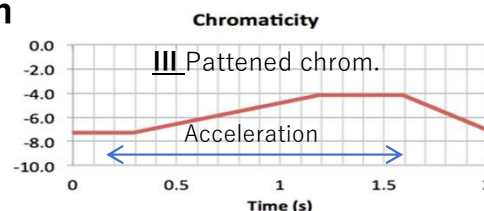
Some of Magnets were designed for the Ring Formerly Known As the 50-GeV Ring → 30 GeV operation

Margin!

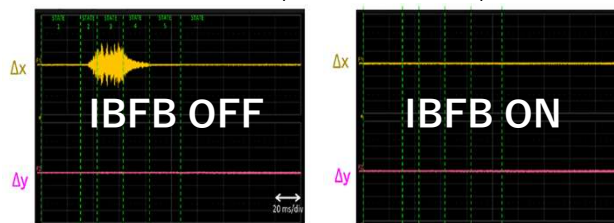
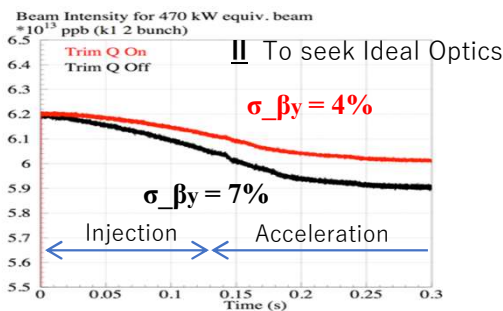
- I. Injection beam quality: optimized RCS parameters, verified at 3-50BT monitors
- II. Optics measurements and corrections needs  $\sigma_{\beta_{x,y}} < 4\%$
- III. Transverse instability suppression: Intra-BunchFB, controlled chromaticity
- IV. 2<sup>nd</sup> harmonic RF to suppress space charge tune spread
- V. Longitudinal beam loading compensation system
- VI. Third order resonance corrections
- VII. Tune optimization (injection & acceleration)
- VIII. ...



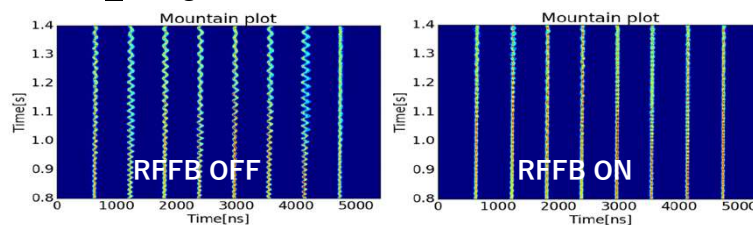
! 6 digit wide range halo monitors



III Beam Position of  $2.1 \times 10^{13}$  ppb \* 2 bunches with Intra-bunch FB (Stripline BPM & Stripline kicker)

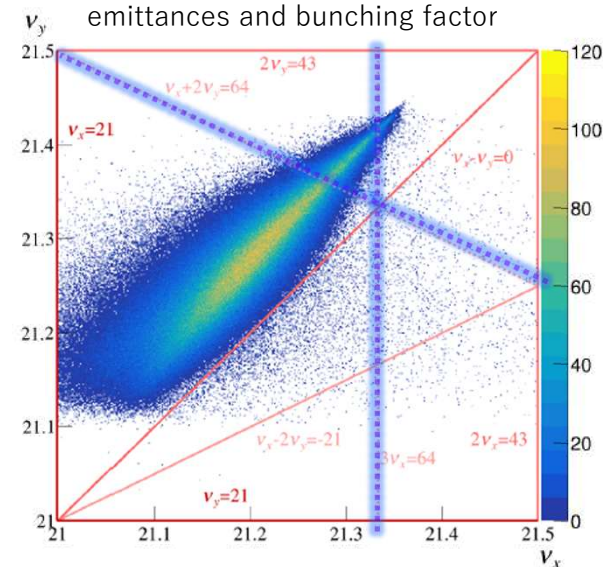


V Long. bunch oscillation of 480 kW beam



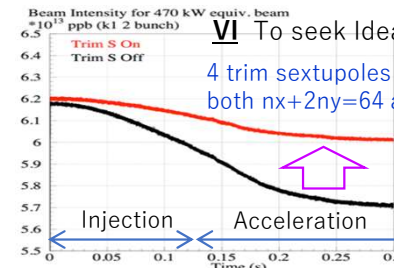
Simulated tune shift of MR Power 500 kW  
(Tune Spread 0.4)

based on the measured transverse emittances and bunching factor



VI To seek Ideal Optics

4 trim sextupoles correct both  $n_x + 2n_y = 64$  and  $3n_x = 64$



See Igarashi's Latest Work:  
Res. Corr. considering SC & Off-mom.

**Keys of  
World record  
protons/pulse  
(2020.1)  
2.7E14 ppp**

**②** Linac/RCS upgrades  
have suppressed beam  
halo into MR (2013,2014)

**③** Longer MR bunch to reduce  
Space Charge Effect after  
applying RF mismatch paint  
and upgrading Inj KM  
system (2014)

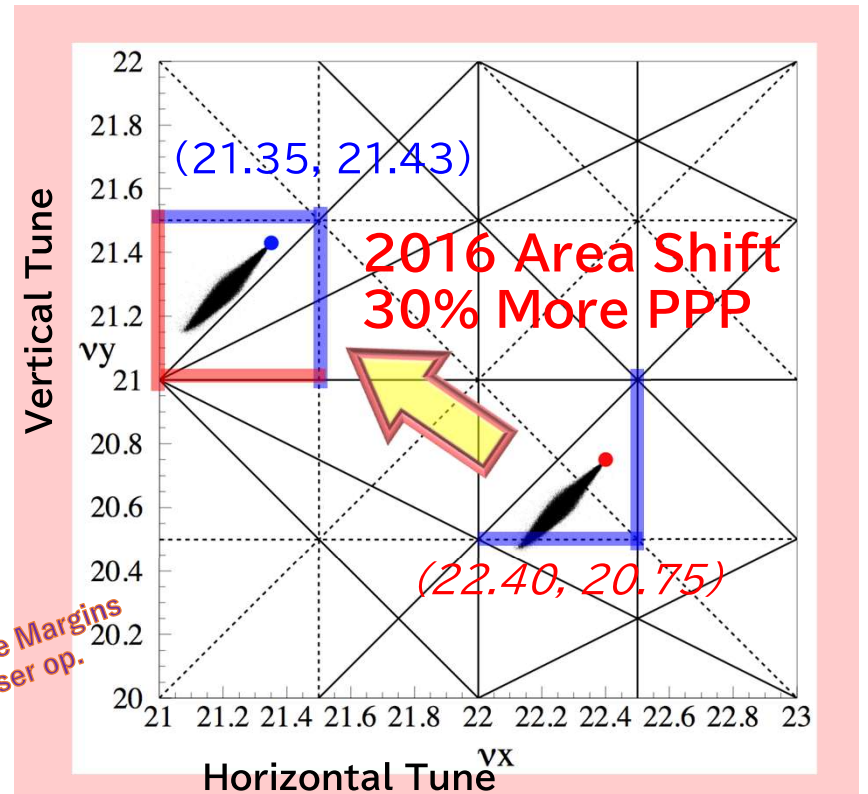
*Bucket  
Margin*

**①**

Seeking Good-  
reproducibility  
even for  
higher power  
(2009~)

**④** MR tune area change in 2016  
required to **challenge the  
margins of MR magnetic PS  
and aperture.**  
Needed 2 year R&D (2014 - 2016)

*Applied the Margins  
into user op.*



栗本佳典、佐藤洋一「J-PARC Main Ring アップグレード」 「加速器」2021 年 18 巻 1 号 p. 10-20 <https://doi.org/10.50868/pasj.18.1.10>

**Twice faster cycle  
& > 2.7E14 ppp  
(Halve loss ratio)**

**⑤**

Upgraded MR Magnet PS system, RF system, ...  
→ **Twice # pulse (halved period)** (2021.7-2022.6)

**⑥**

Discovered New Optics (2022), Applied it in user  
operation (2025), Halved beam loss ratio (2026 -)

*Upgrades holding  
Some Margins*

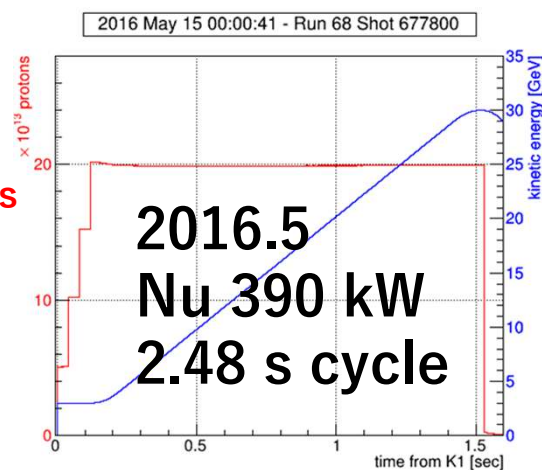
# MR-FX Beam Quality

2023-4-16  
Achieved  
FX 750 kW  
(Design Power)

Protons

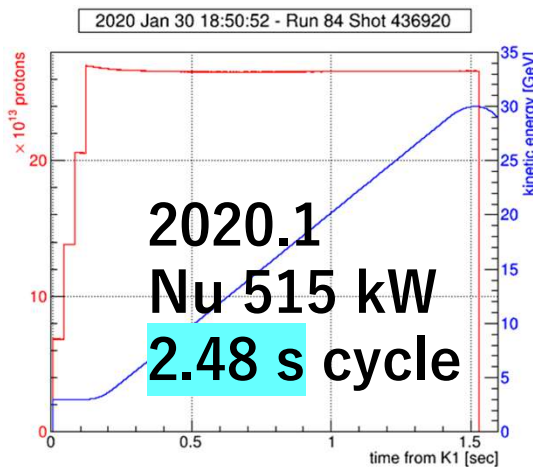
K.E.

Beam  
loss



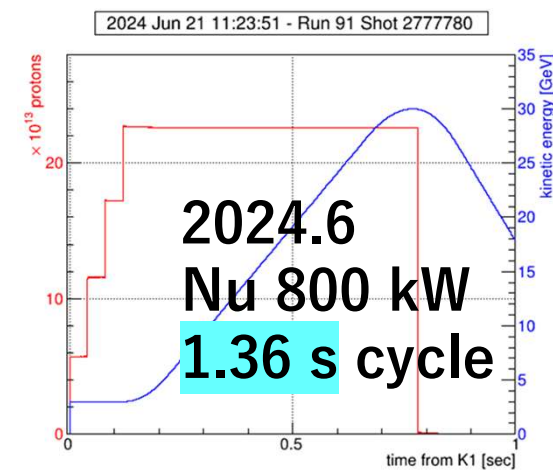
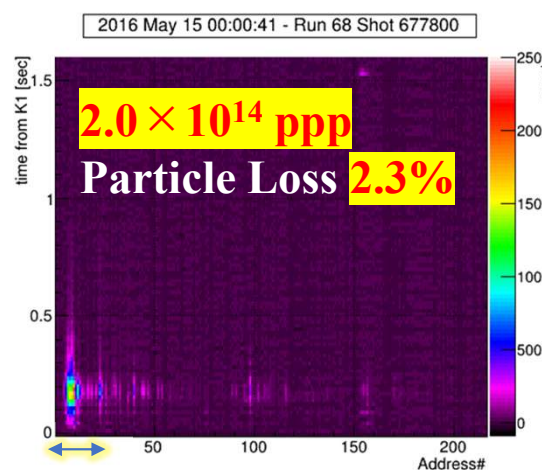
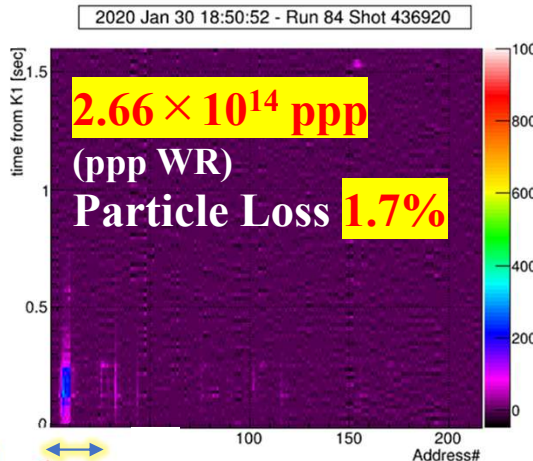
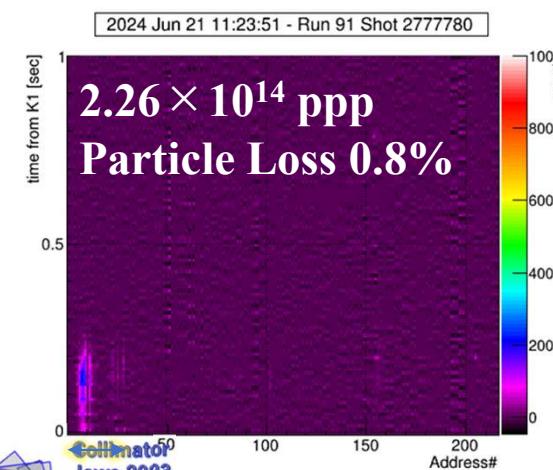
④

New  
Optics

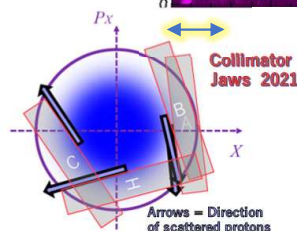


⑤

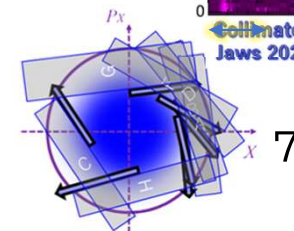
High rep.  
Upgrades



Gain 1/8  
In Collimator Area  
(Beam Loss localized)



4 ring collimators



7 ring collimators

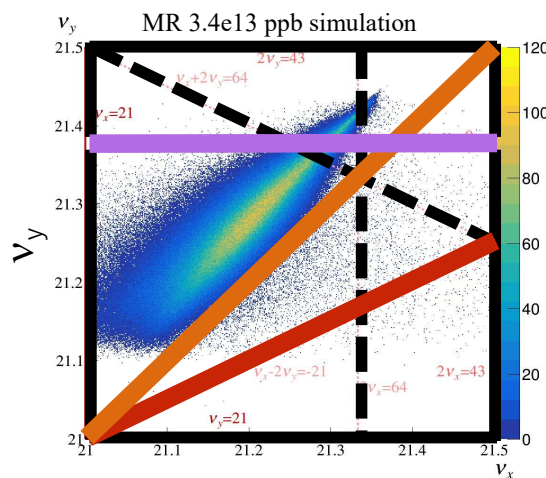
Simplified image of betatron oscillation

$$\ddot{x} + \omega_{x0}^2 x = \sum_n F_{xn} \cos(\omega_{xn} t + \phi_{xn})$$

$$\ddot{y} + \omega_{y0}^2 y = \sum_n F_{yn} \cos(\omega_{yn} t + \phi_{yn})$$

$n$  : resonances  
 $F$ : function of  $x, y$

$\omega_{x0}$  have wide  
 $\omega_{y0}$  distribution  
(Tune spread)



T. Yasui, et. al.,  
PRAB **23**, 061001 (2020).

**\*1 for  $n_x - 2n_y = -21$**

T. Yasui, S. Igarashi, Y. Sato, and T. Koseki,  
“Beam optics for the compensation of third-order structure resonances”,  
Prog. Theor. Exp. Phys. **2022**, 013G01 (2022).  
<https://doi.org/10.1093/ptep/ptab146>

**\*2 for  $8n_y = 171$**

T. Yasui and Y. Kurimoto,  
“Suppression of the eighth-order space-charge-induced resonance”,  
Phys. Rev. Accel. Beams, **25**, 121001 (2022).  
<https://doi.org/10.1103/PhysRevAccelBeams.25.121001>

Non-systematic resonances --- can be compensated with correction magnets.

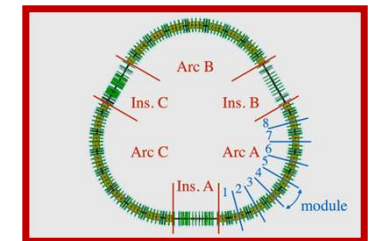
$$F_1 \cos(\omega_1 t + \phi_1) + c_\alpha \cos(\omega_1 t + \phi_\alpha) + c_\beta \cos(\omega_1 t + \phi_\beta) = 0$$

Systematic resonances --- driven by sextupole magnets and space charge effects.

$$F_1 \cos(\omega_1 t + \phi_1) = \sum_{p=1}^3 \sum_{q=1}^8 f_1 \cos(\omega_1 t + \varphi_{p,q})$$

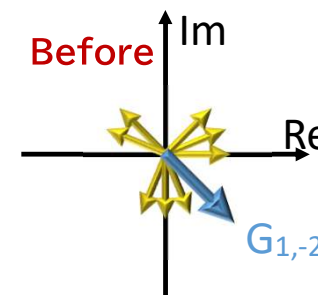
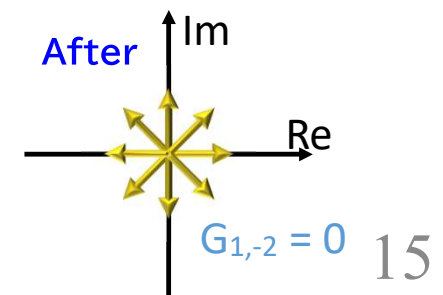


**0 (for any  $f_1$ ) under proper phases**



$$\sum_{q=1}^8 \cos(\omega_1 t + \varphi_{p,q}) = \cos(\omega_1 t + \varphi_{p,1}) + \cos(\omega_1 t + \varphi_{p,1} + \frac{2\pi k}{8}) + \dots + \cos(\omega_1 t + \varphi_{p,1} + 7\frac{2\pi k}{8}) = 0$$

See Yasui's



# MR-FX Beam Quality

2020.1.30 NU 515 kW

$2.66 \times 10^{14}$  ppp

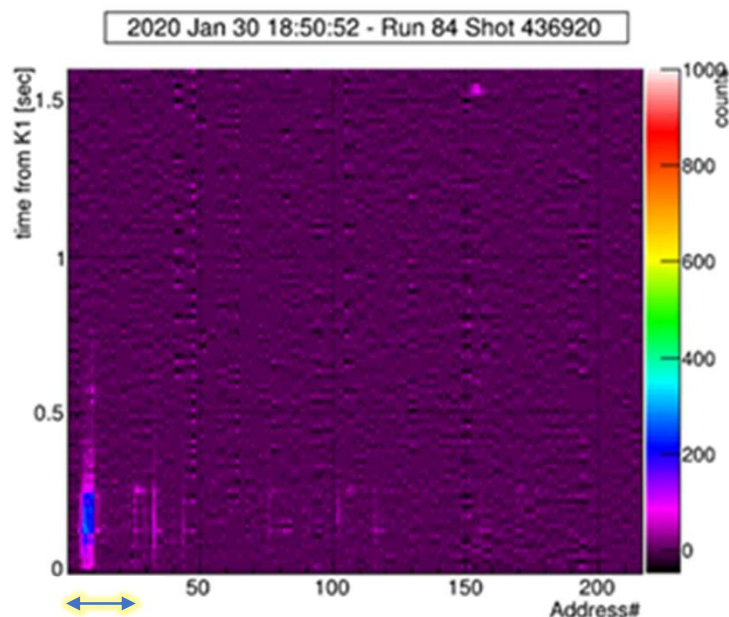
(ppp WR)

Particle Loss 1.7%

2.48 s Cycle

⑤

Higher  
repetition



Gain 1/8  
In Collimator Area  
(Beam Loss localized)

2026.2.19 NU 1 MW demo

$2.68 \times 10^{14}$  ppp

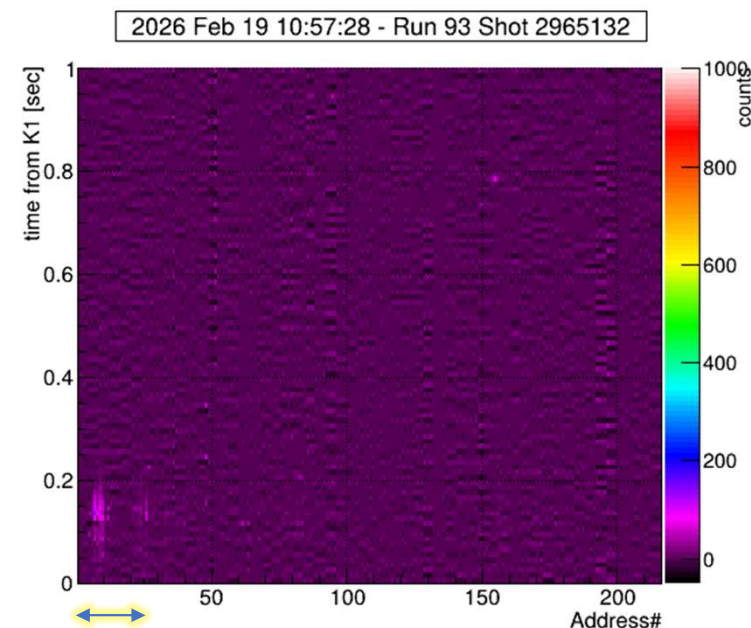
(ppp WR again!)

Particle Loss 1.1%

1.28 s Cycle

⑥

New  
Arc  
Lattice



Gain 1/64  
In Collimator Area  
(Beam Loss localized)

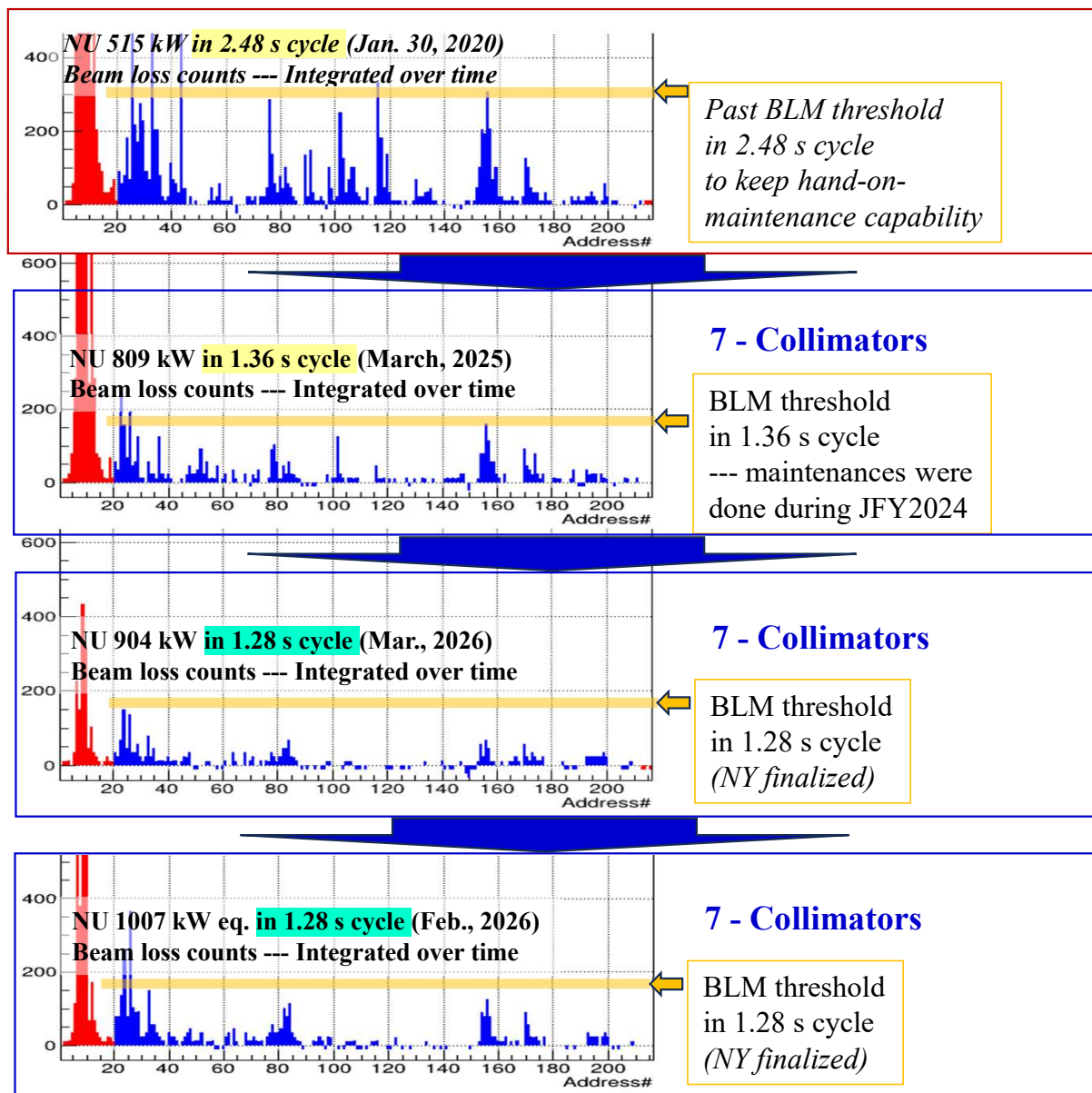
# Beam loss localization

| JFY  | Beam Power User Op. | Cycle Time | Beam Intensity            | Particle Loss (DCCT estimation) |
|------|---------------------|------------|---------------------------|---------------------------------|
| 2019 | 515 kW              | 2.48 s     | $2.66 \times 10^{14}$ ppp | 1.7%                            |
| 2023 | 760 kW              | 1.36 s     | $2.20 \times 10^{14}$ ppp | 1.6%                            |
| 2024 | 809 kW              | 1.36 s     | $2.29 \times 10^{14}$ ppp | 0.9%                            |
| 2024 | 830 kW              | 1.36 s     | $2.35 \times 10^{14}$ ppp | 1.5%                            |
| 2025 | 900 kW              | 1.28 s     | $2.40 \times 10^{14}$ ppp | 0.5%                            |
| 2025 | 1 MW                | 1.28 s     | $2.68 \times 10^{14}$ ppp | 1.1%                            |

## Present scenario of collimator balancing

- Consider single path collimation first, then optimize the balance empirically
- Upstream collimators are set in smaller aperture. Downstream collimators are basically set to catch scatt. particles.
- Scattered particles at collimators are minimized by angled col-jaws.

FX is aiming 1.3 MW by JFY2028



Collimators are mostly optimized.

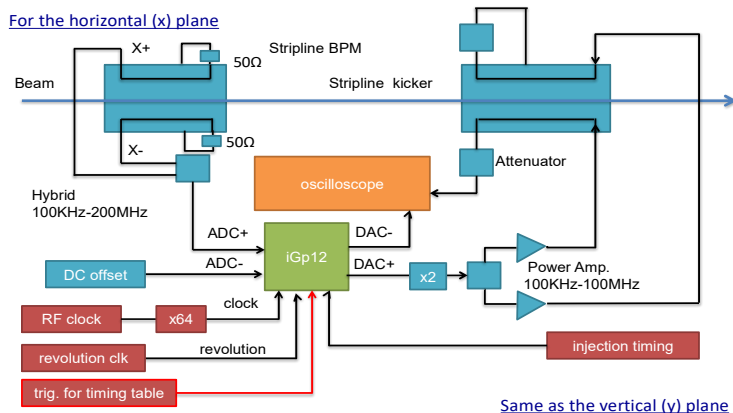
**Mission: Provide the diagnostics for realization of 750 kW – 1.3 MW beam operation in the J-PARC MR**

## Eyes to aim 1.3 MW:

New BLM signal processing circuit, Abort profile monitor and 16-electrodes monitor have newly started operation. DCCT covers 2.7 e14 ppp with factor 2 margin. All diagnostics devices contributed to beam power upgrade from 450 to 510 kW in 2018.

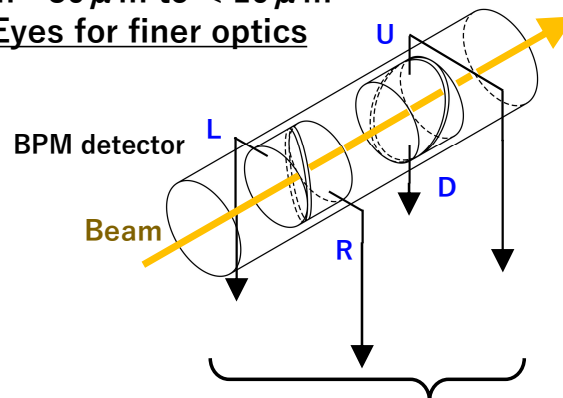
## Task(1) Upgrade of the intra-bunch feedback

### Shorten the damping time (>30%)

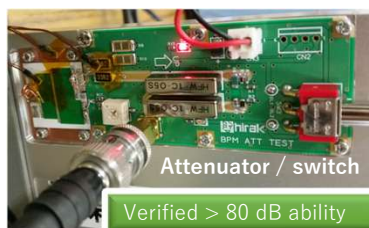


## Task (2) Upgrade of the BPM circuits

Improve the position accuracy from  $\sim 30 \mu\text{m}$  to  $< 10 \mu\text{m}$   
 -> Eyes for finer optics

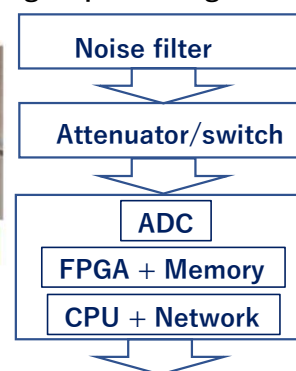


Develop New Signal Acquisition System



Large Data Storage is needed also

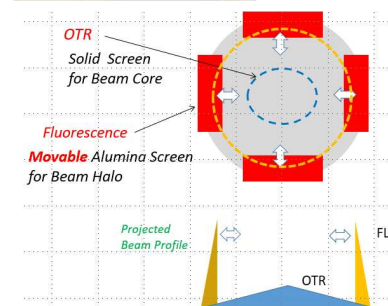
Signal processing circuit



## Task(3) OTR profile monitor in the MR

Measure the 2D profile and halo of the injected beam into the MR  
 -> Eye for Halo collimation by COLs  
 -> Eye for Halo reduction by optics

Motion mechanism for the target  
 Ti-foil for the OTR & fluorescent plate

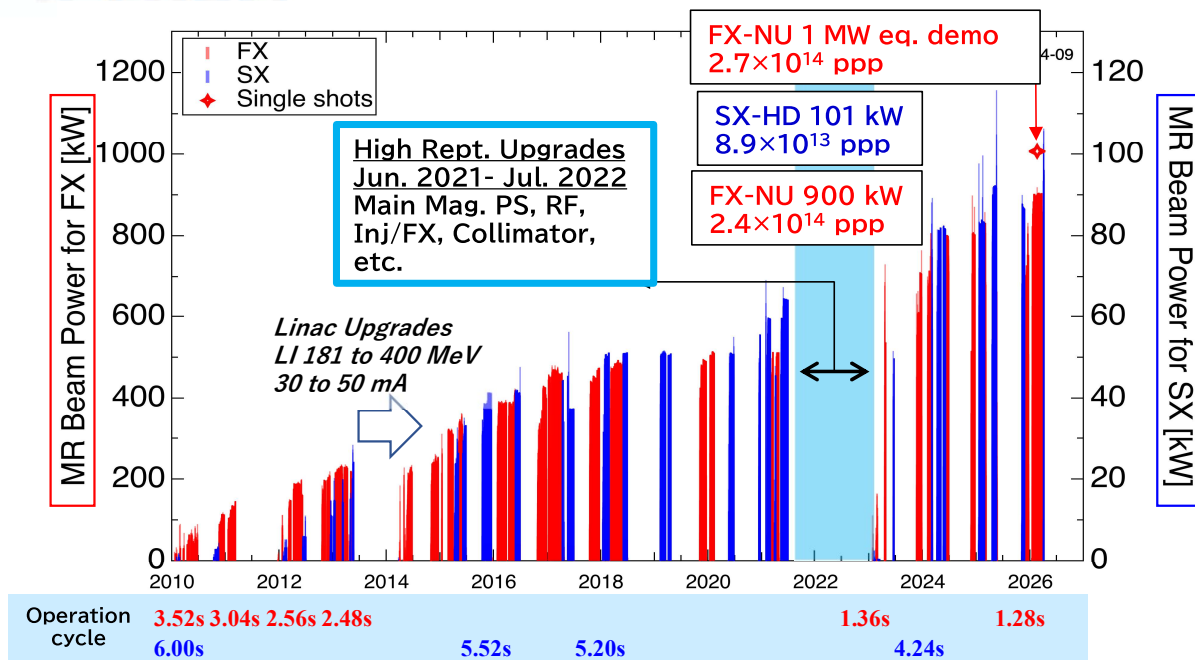
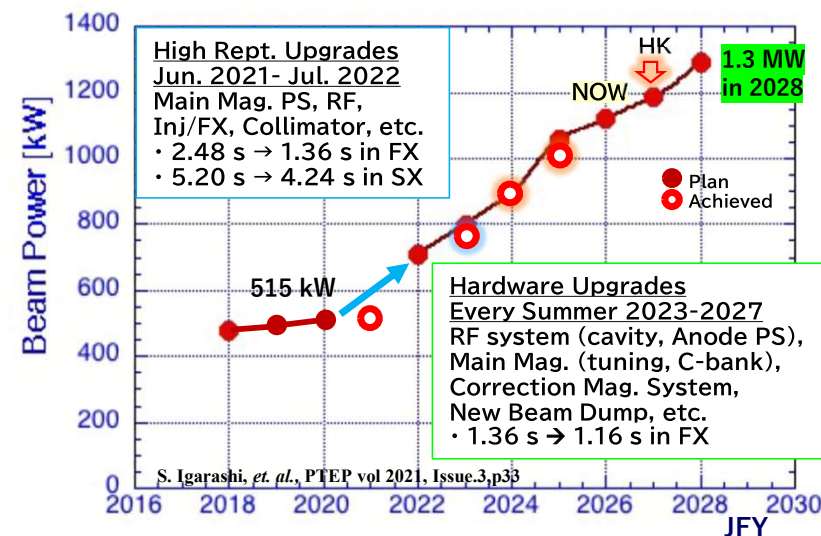
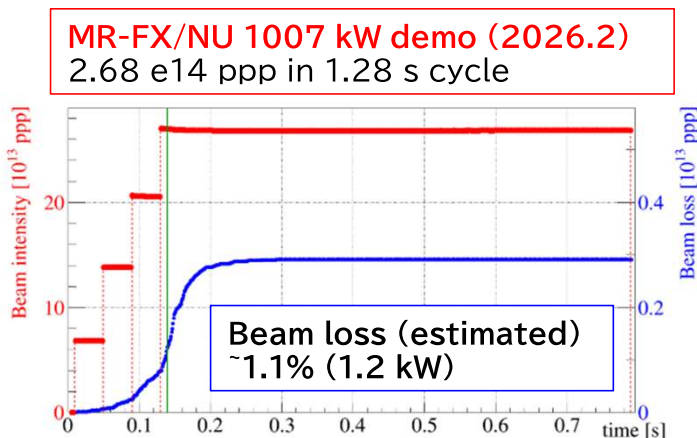


Same type monitor (3-50BT-OTR/FL) realized dynamic range  $10^{-6}$

New MR-OTR/FL needs high radiated durability and much less impedance.

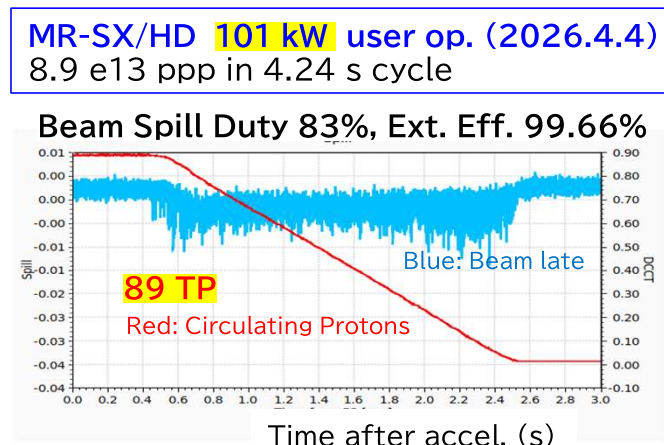
**To aim higher power, Good Eyes are ALWAYS important!**

# MR Power Trend and Near Future Plan



**FX is aiming 1.3 MW by JFY2028**

**Keeping beam loss <~ 1%**



**SX is aiming >150 kW (TGT upgrade 2031~) and Higher Spill Duty**

# Discussion for Our Future

Q: How to design a next-generation highest-intensity facility?  
from the particular view point of the A-4 session topic  
“Beam loss & halo dynamics”

Y.S. believes  
Isolate the problems as much as possible  
and  
tackle them one by one  
That's the basics of beam tuning.

**Initial Works** are very important.  
**Securing Margines** is the Cradle of Higher Power.  
**The Margines** help Good **Post Works**

**Challenge cost limits ALWAYS to earn margines for our future!**

## **A-4 Session “Beam loss & halo dynamics”**

13:30 - 13:50 Yoichi Sato  
Session Chair

Lead talk: Beam Loss and Halo Dynamics  
Session Question  
Answers of J-PARC Main Ring

13:50 - 14:05 Trent Thompson

Observations of mismatch-driven halo  
in 2.5 MeV H- beam at the SNS Beam Test Facility

14:05 - 14:20 Shouyan Xu

Space Charge Effect Simulation and Tune Optimization  
for Reducing Beam Loss at CSNS

14:20 - 14:35 Esmaeil Ahmadi

Experimental and Simulation Studies of  
Non-linear Resonances in the ISIS Synchrotron

14:35 - 15:00 Yoichi Sato  
Session Chair

Discussion Session A-4

# Discussion for Our Future

Q: How to design a next-generation highest-intensity facility?  
from the particular view point of the A-4 session topic  
“Beam loss & halo dynamics”

**Beam halo** in A-4 = a part of beam touching physical aperture or collimators

## To reduce the beam halo development

### Measures

- A) Enlarge physical / dynamic aperture
- B) Avoiding / killing transition energy
- C) Avoiding the betatron resonance lines
- D) Suppressing betatron resonances
- E) Removing resonance sources
- F) Linear mitigation of SC

### Initial Design

- Main devices ✓
- Arc design ✓✓
- Base Tune ✓✓
- Place of post-works
- Lattice design?
- Higher energy ✓

### Post Design + Study Time

- Optics Improvement ✓
- 
- Tune survey ✓✓
- Adding Corrections ✓✓
- Lattice Re-design? ✓
- Longitudinal control ✓✓

Enough?

## Measures for insability, beam loss source but not from the beam halo development

Impedance budget control, Sllipage opt., FB system, Chromatic control, Longitudinal control, ...



Mixture of *initial* and *post* works

Enough?

**Initial works are very important, but Post works can perform some using Margines.**

**Challenge cost limits always to earn margines for our future!**

Agree? 22

Additional slides

# Japan Proton Accelerator Research Complex



## LINAC

- Length: 249 m
- Kinetic Energy: 181 → 400 MeV  
v/c 71%
- Current 30 → 50 mA (→ 60~70 mA)
- Inject H<sup>-</sup> into 3 GeV Synchrotron

Higher current  
Higher energy  
Upgraded 2013-14



## 3 GeV Synchrotron (RCS)

- Circumference: 348 m
- Kinetic Energy: 3 GeV  
v/c 97%
- Beam Power 1 MW (→ 1.5~2 MW)
- 90~95% protons into MLF
- 10~5% protons into MR

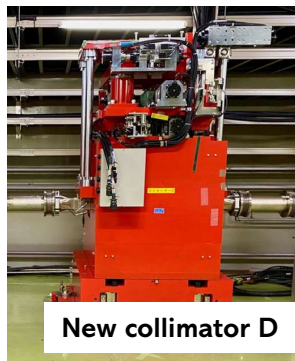
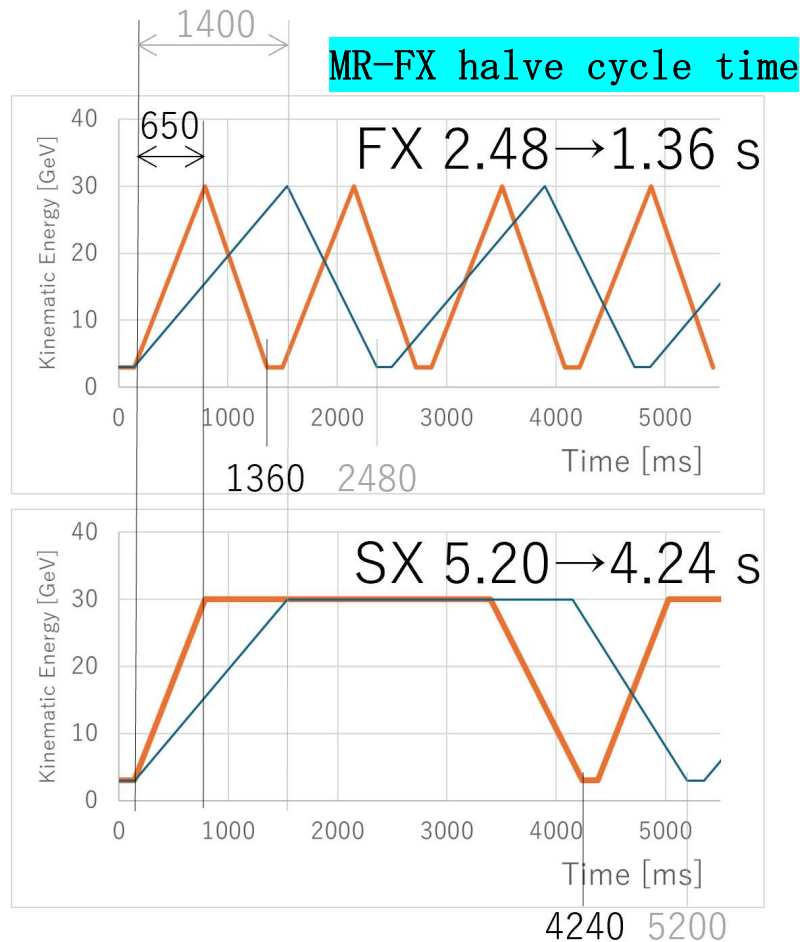


## Main Ring (MR)

- Circumference: 1,568 m
- Kinetic Energy: 30 GeV  
v/c 99.95%
- Beam Power 0.9 MW (→ 1.3 MW)
- Provide protons to NU/HD



# ⑤MR Higher Repetition Upgrades in 2021-2022



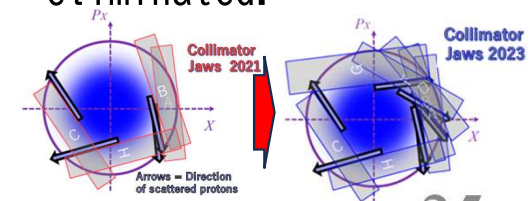
Beam Power  $\propto$

Protons/pulse  
Cycle time

$\times$  Beam Energy

Utilizing extensively upgraded equipment mainly RF and Magnet (momentum =  $B \cdot \rho$ ) for Faster acceleration

By adding collimators, halos can be efficiently eliminated.



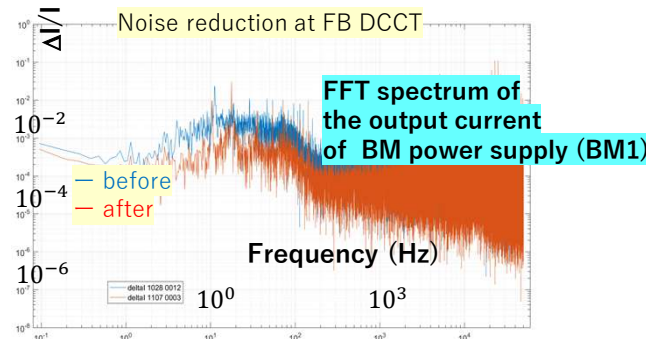
# ⑤MR Higher Repetition Upgrades in 2021-2022

Past talks for J-PARC MR:  
 •H. Hotchi, J-PARC symposium 2024  
 •Y. Sato, HB2023



MR-FX Twice faster cycle  
 MR-SX 20% faster cycle

•Less ripple in New Mag PS  
 Suppress the effect of non-structure res. basically



•Seeking Optics Symmetry  
 New scheme enabled  
 $\Delta\beta/\beta < 2\%$   
 $\Rightarrow$  Suppress particle loss

New scheme development  
 Optics meas. / corr.  
 T. Asami, et. al.,

$$\text{Beam Power} \propto \frac{\text{Protons/pulse}}{\text{Cycle time}} \times \text{Beam Energy}$$

## Re-cabling of Mag PS

